NUCLEI 01? COMET SHOEMAKER-LEVY 9 ON IMAGES TAKEN WITH THE HUBBLE SPACE TELESCOPE

Zdenek Sekanina

Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California 91109, U.S.A.

ABSTRACT

Central regions on the digital maps of 13 condensations of Comet Shoemaker-Levy 9, obtained with the Planetary Camera of the Hubble Space Telescope in January, March, and July 1994, have been analyzed with the aim to search for major fragments, to deconvolve their contributions to the signal that also includes the light scattered from dust in a surrounding cloud, to estimate their dimensions, and to determine their spatial distributions in the comae as projected onto the plane of the sky. It is found that sizable fragments apparently survived until the time of atmospheric entry, a result that does not contradict evidence on the comet's continuing fragmentation. On plausible assumptions, the largest fragments are found to have had effective diameters of ~4 km as late as the beginning of July 1994. Sizable companions (N I km or more across) were detected in most condensations within ~1000 km of the projected location of the brightest fragment, with the surrounding dust cloud centered on a point that is shifted in the genera] direction of the tail, an effect of solar radiation pressure.

1. INTRODUCTION

The nuclear size is one of the fundamental bulk properties of every comet. Its knowledge is essential not only for our understanding of the object's observed physical behavior, but is also critical for theories of comet formation and long-term evolution. In the case of Comet Shoemaker-Levy 9 (1993e), a further intent ive for pursuing all avenues available to addressing this problem was provided by the need to interpret the observed events that accompanied the comet's collision with Jupiter in July 1994. The masses of the major fragments, closely related to their dimensions, are the only inadequately known quantities preventing us from deriving reliable estimates for the kinetic energies of the individual nuclei and for the total energy deposited by them in the jovian atmosphere.

Estimates for the nucleus diameter of the parent comet and/or its fragments found in the literature (Scotti & Melosh 1993; Weaver *et* al. 1994; Asphaug & Benz 1994; Chernetenko & Medvedev 1994; Solem 1994; Sekanina *et al.* 1994) fall into two distinct groups, corresponding to 1--2 km and 7-10 km for the parent.

2. THE PROBLEM

The sizes of some of the comet's fragments are derived in this study photometrically from images obtained between January 24 and July 4, 1994 with the Planetary mode Charge Coupled Device (CCD) of the Wide-Field Planetary Camera 2 (WFPC-2) of the Hubble Space Telescope (HST), whose pixel size equals 0.0455 arcsec. The basic *modus operandi* can be compared with that of Weaver *et al.* (1994) and the reader is referred to this paper for information on the image calibration and processing. However, the analytical approach, applied here to extract the contributions from major fragments hidden in the surrounding cloud of dust, is very different from Weaver *et al.*'s technique.

The observed surface-brightness distribution in each condensation can in general be considered to consist of a convolved sum of contributions from a number of point sources (major fragments) and a number of extended sources (which make up the surrounding cloud of minor fragments and other particulate material). Available in practice were digital maps of brightness distributions in fields of 15 pixels, or 0,7 arcsec, across and centered on the peak pixel. With the exception of the condenstaion S, no major deviations from an isotropic decrease in brightness from the peak pixel toward the field's edges were present on these maps. Samples of 157 pixels within a circle 15 pixels in diameter and centered on the peak pixel were employed.

The following description is limited to models with a multitude of point sources and a single extended source, because tests showed that all solutions involving more than one extended source encountered intractable convergence difficulties. The approach has two important features: (a) it allows the location of the extended source's brightness peak to differ from the location of any of the point sources and (b) it also allows pixel interpolation, taking into account the fact that the location of any source (including the peak of the extented source) does not generally coincide with the center of a pixel. Instead, the coordinates of the source locations are solved for by least squares along with the other parameters (Secs. 3-4). in practical applications, these two features were found to be indispensable for a successful solution optimization,

3. THE POINT SOURCES

Let $B(X, Y)$ be the observed amount of light impinging on a square-shaped pixel in a row X and a column Y, measured in CCD analog-to-digital intensity units (ADU). The problem is to find summary contributions from the individual point sources and the extended source to the observed brightness distribution by integrating them over all pixels in the field and to determine the dimensions (effective diameter) of each point source from its integrated signal and an assumed albedo.

Consider first point sources. The need to solve for the location of each source and to maintain the problem easily tractable dictated that a simple empirical function be found that would reasonably well fit a model point spread function's (PSF) pixel-signal distribution that was available in tabular form. After extensively experimenting with a wide variety of candidate functions, I settled on the following quasi- Gaussian approximation for the PSF's surface-brightness distribution law $b_{\rm psf}(x, y)$, expressed in ADU per arcsec^2:

$$b_{\rm psf}(x,y) = b_* \exp\left[-\left(\frac{x^2+y^2}{2\sigma_{\rm psf}^2}\right)^{\nu_{\rm psf}}\right], \tag{1}$$

where $\sigma_{\rm psf} > 0$ is the PSF's dispersion parameter (in arcsec), $\nu_{\rm psf} > 0$ is a dimensionless constant ($\nu_{\rm psf} = 1$ for the Gaussian function), and $(x^2+y^2)^{\frac{1}{2}} = \rho$ is the angular distance (in arcsec) from the PSF's peak. The surface brightness at the peak is $b_{\rm psf}(0, 0) = b_*$. The total signal, or the integrated brightness, I_* of a point source is, in ADU,

$$I_* = 2\pi \int_0^\infty \rho \, b_{\rm psf}(\rho) \, d\rho = 2\pi b_* \sigma_{\rm psf}^2 \nu_{\rm psf}^{-1} \Gamma(\nu_{\rm psf}^{-1}), \tag{2}$$

where $\Gamma(z)$ is the Gamma function of argument $z > 0$. If $\{X_*, Y_*\}$ are the pixel location numbers of a given source (or its PSF's peak signal), the coordinates of the center of an

$\{X, Y\}$ pixel relative to this source are $x = H(X - X_*)$ and $y = H(Y - Y_*)$, where H is the pixel size in arcsec. The pixel locations $\{X, Y\}$ have been defined by assigning the coordinates $\{10, 10\}$ to the center of the peak pixel.

Applied to the available PSF pixel distribution for a point source whose $I_* = 500$ ADU (close to the maximum integrated brightness encountered among the studied fragments), the introduced approximate solution yielded, with $H = 0.0455$ arcsec, the following best-fit parametric values: $\sigma_{psf} = 0.0112 \pm 0.0009$ arcsec, $\nu_{psf} = 0.347 \pm 0.011$, and therefore $I_* = 0.004085\, b_*$. The PSF's contribution of 93.4 ADU to the brightest pixel represents 18.7 percent of the entire signal and implies a peak surface brightness of 253 ADU/pixel^2 or, equivalently, 122,000 ADU/arcsec^2. The source's introduced position was recovered with a formal precision of 0.03 pixel or 0.001 arcsec, an error much smaller than the actual uncertainties involved. The solution leaves a mean pixel-signal residual of ± 0.86 ADU and a maximum residual of 3 ADU, which is slightly lower than the expected peak noise assuming no contribution from flat-fielding and about $\frac{1}{2}$ the expected peak noise if the flat-fielding noise is 5 percent of the signal. Measured by these standards, the employed quasi-Gaussian law should be considered as more than adequate for the purposes of this study, which was confirmed by testing it against a more elaborate approximation law.

4. THE EXTENDED SOURCE AND THE SOLUTION

Two different laws have been considered for the surface-brightness distribution $b_{ext}(\rho)$ of the extended source. Convoluted with the PSF, the laws are assumed in the form:

$$\text{Law A}: \quad b_{ext}(\rho) = \frac{b_0}{1 + (\rho/\sigma)^\nu}, \qquad \text{Law B}: \quad b_{ext}(\rho) = b_0 \exp\left[-\left(\frac{\rho^2}{2\sigma^2}\right)^\nu\right], \tag{3}$$

where ρ is the angular distance from the point of peak surface brightness, $b_{ext}(0) = b_0$, of the extended source, located at a pixel position $\{X_0, Y_0\}$. The dispersion σ and the exponent ν (analogous, in the case of the law B, to σ_{psf} and ν_{psf}), as well as b_0, X_0, and Y_0 are constants to be determined by a least-squares differential-correction procedure. The $\{x, y\}$ coordinates of an $\{X, Y\}$ pixel relative to the peak of the extended source have been defined as in the case of a point source.

The observed pixel-signal distribution can now be modeled as a sum of the contributions from n point sources and the extended source. If the pixel location of an ith point source is given by $\{(X_*)_i, (Y_*)_i\}$ and its surface-brightness distribution by $b^{(i)}_{psf}(x, y)$, the modeled distribution is calculated by the following integration over each pixel's area:

$$B(X, Y)$$
$$= \sum_{i=1}^{n} \left\{ \int_{H[X-(X_*)_i-\frac{1}{2}]}^{H[X-(X_*)_i+\frac{1}{2}]} dx \int_{H[Y-(Y_*)_i-\frac{1}{2}]}^{H[Y-(Y_*)_i+\frac{1}{2}]} b^{(i)}_{psf}(x, y)\, dy \right\} + \int_{H(X-X_0-\frac{1}{2})}^{H(X-X_0+\frac{1}{2})} dx \int_{H(Y-Y_0-\frac{1}{2})}^{H(Y-Y_0+\frac{1}{2})} b_{ext}(x, y)\, dy, \tag{4}$$

where the location of the peak of the extended source is allowed to differ from the location of any of the considered point sources, $X_0 \neq (X_*)_i$ and $Y_0 \neq (Y_*)_i$, $(i = 1, \ldots, n)$.

An initial solution for $B(X, Y)$ that includes n point sources and an extended source has $(3n+5)$ parameters: $(I_*)_1, \ldots, (I_*)_n, (X_*)_1, \ldots, (X_*)_n, (Y_*)_1, \ldots, (Y_*)_n, b_0, \sigma, \nu, X_0$, and Y_0. It serves as a starting point of an iterative, least-squares differential-correction procedure that allows one to iterate the solution until it has converged. If noise in the input data impedes the convergence, one should first solve for only some of the parameters and expand the number of parameters to $(3n + 5)$ gradually, after the convergence is reached when solving for fewer than the full number- of parameters. The quality of fit is determined by inspecting the pixel distribution of residuals from the solution and by comparing it with the expected instrumental noise variations. The ultimate goals of the error analysis effort arc to discriminate as fully as possible between genuine unresolved sources and artifacts of the applied procedure and to estimate the uncertainties involved.

5. THE RESULTS, DISCUSSION, AND CONCLUSIONS

The described approach has been applied to digital maps of the brightness distribution in several nuclear condensations of Comet Shoemaker-Levy 9, as observed with the HST Planetary Camera, The effective diameters of the fragments arc determined from their R magnitudes (derived from the ADU units and the exposure time with the use of a transformation formula), assuming a geometric albedo of 0.04 and a phase coefficient of 0.035 mag/deg. On these assumptions, the formal 1 σ error in the calculated diameters is typically ± 0.1 to ± 0.2 km, but, realistically, diameters $\lesssim 1$ km can be at best only marginally detected. independent runs made with the two laws for the extended source showed similar results, the: law A yielding slightly bet tcr residuals.

For each condensation '1'able 1 lists the effective diameter of the largest fragment and the number of companions detected on the images taken on the three dates. The dots indicate that no appropriate data were available. Although varying from case to case, the largest fragment was typically found to contribute about 50 percent of the light in the peak pixel, the extended source making up the rest. Companions often accounted for significant fractions of the light in small clumps of pixels on the sample's outskirts.

TABLE 1
Effective Diameters of Largest Fragments and Numbers of Companions From HST Observations (Extended Source Subtracted Using Law A).

Condensation	Largest object's effective diameter (km)			Number of detected companions		
	Jan. 24--25	Mar. 28-30	Jul. 4	Jan. 24-25	Mar. 28-30	Jul. 4
F	2.3	2.1	...	1	1	...
G	4.3	3.7	...	4	3	...
11	3.3	...	...	3	...	
N	1.6	1.4	...	0	0	...
1'1	1.3	0.6	...	2	0	...
P*	2.4	1.4	...	5[a]	4	...
Q_1	4.0	2.9	3.9	5	2	5
Q2	3.2	1.5	2.5	2	3	3
R	2.7	2.1	...	0	2	...
s	3.6	2.5	...	8	6[b]	...
T	1.4		...	1	...	...
U	1.3	1'.0	...	0	0	...
v	$\ll 1$	...	...	0	...	...

[a] Effective diameter of the largest companion is 2.1 km.
[b] Effective diameter of the largest companion is 2.3 km.

The results of this investigation indicate that prolific fragmentation of the comet's nucleus continued for a considerable period of time after the initial tidal breakup in July 1992, so that the dimensions of the individual fragments were time dependent. The process of fragmentation, while essentially continuous taken stochastically, appears to have proceeded-—at least in its early stages, involving large, kilometer-sized fragments—in the form of discrete events, which can readily explain the repeatedly observed instances of sudden, short-term brightening of the various condensations. There is little doubt that, as a result of the fragmentation events recurring over and over again, many of the objects eventually disintegrated to the extent that they could no longer be detected individually even on a condensation's digital map and, sooner or later, they merely contributed to the surrounding dust cloud. However, available evidence shows that, in spite of the progressive fragmentation, one dominant fragment persisted in most condensations. Two striking exceptions to this rule are provided by the condensations P_2 and S. Weaver (1994a, b) remarked on a peculiar appearance of both of them: P_2 was clearly double on March 30, 1994, while a "spur" extending from S to the south was seen both on January 24 and March 30, but was brighter on the first date. The present analysis suggests that the two major components of P_2 were present already in late January, 0,135 arcsec apart, with the fainter one at a position angle of 235°. The spur of the fragment S appears on digital maps to have consisted of four approximately aligned components 0.08 to 0.31 arcsec away from the brightest fragment on January 24 and the two innermost companions may have been identical with some of the fragments detected two months later. By then, however, the primary nucleus of S was found to have broken into two about equally bright components, separated by 0,05 arcsec, or some 160 km in projection onto the sky plane, and each of a calculated effective diameter of ~2.5 km. The slightly fainter one of the two was at a position angle of ~140°.

The distributions of companions in the other condensations did not display any striking patterns, Generally, however, the number of companions correlated with the size of the largest fragment, as is apparent from Table 1. Projected distances between companions *were* typically hundreds of kilometers and up to 1000-1500 km.

Although the dimensions of individual fragments must obviously have diminished with time, no systematic rate of decrease could be established from the available data between late January and early July 1994. In fact, shortly before their crash on Jupiter, the largest fragments were still found to have effective diameters comparable with those derived by Weaver *et al.* (1994) from the HST observations in July 1993 and consistent with the dimensions of the comet's parent nucleus proposed by Sekanina *et al.* (1994). The rate of decrease in the sizes of the large fragments, implied by their continuing breakups, appears to be much less significant than rotation variations in the projected cross-sectional area of these objects which undoubtedly were extremely irregular.

The dust clouds in most of the condensations were found to be centered on points usually a few pixels to the west of the brightest fragments, which was the direction of the tails and which is consistent with the presence of *a* slight cumulative effect due to solar radiation pressure from the time of tidal breakup in July 1992. Such an effect is not surprising, if the brightness of the clouds was dominated by centimeter-sized pebbles,

The evidence presented in this study leads to the following conclusions: (1) the steep slope of the observed surface-brightness distribution in the immediate proximity of the peak pixel is due primarily to the presence of an unresolved source a major fragment—

and not an effect, of the spatial density of particulates that increases rapidly toward the center of the dust cloud; (2) the derived signals of the major fragments are rather insensitive to the approximations employed for the PSF and for the brightness distribution in the extended source; and (3) the largest fragments detected on three different dates between late January and early July 1994 are about 4 km across for an assumed geometric albedo of 4 percent and a phase coefficient of 0.035 mag/deg. These conclusions corroborate the earlier findings by Weaver *et al.* (1994) and confirm my preliminary results on the continuing presence of massive objects in the condensations, as published shortly before the impacts with Jupiter (Sekanina 1994), but they appear to be contrary to Weaver's (1994a) more recent conclusions and are grossly incompatible with all estimates of less than about 7--8 km for the effective diameter of the progenitor cornet.

The findings on the companion fragments are less conclusive. Relative to the major fragments, the intrinsic brightness of these objects is generally less well determined and the existence of some of them may even be in doubt. Because. of these uncertainties and because of potentially hidden instrumental effects that might affect the conclusions of the present investigation, it is prudent to view the results presented here as still somewhat preliminary. However, I submit that evidence underlying the fundamental conclusions of this study is robust and that any circumstances severely affecting them would have to be substantial, In any case, one cannot err by expressing belief that attention will remain focused on the problem of analysis of the HST digital maps as onc of the most hopeful avenues in our quest for solving the problem of the dimensions of- and the energy deposited in the jovian atmosphere by---Comet Shoemaker-Levy 9.

6. ACKNOWLEDGEMENTS

I thank H. A. Weaver for his kindly providing digital maps for tile 13 nuclear condensations of Comet Shoemaker--Levy 9, which were secured with the WFPC-2; for extensive information on the processing, calibration, and noise characteristics of the HST images; and for his expert comments on the results of the present investigation. I also thank M. F. A'Hearn for his helpful critique, This work is based on observations made with the NASA/ESA Hubble Space Telescope obtained at the Space Telescope Science Institute (STScI), which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Aeronaut ics and Space Administration. This research was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration and was supported in part through Grants GO-5021 and GO-5624 from the STScI.

REFERENCES

Asphaug, E. & Benz, W. (1994). *Nature* **370**, 120.

Chernetenko, Y. A. & Medvedev, Y. D. (1994). *Planet. Space Sci.* 42, 95.

Scotti, J. V. & Melosh, H. J. (1993). *Nature* 365, 733.

Sekanina, Z. (1994). *IAU Circ. No.* 6020.

Sekanina, Z., Chodas, P. W. & Yeomans, D. K. (1994). *Astron. Astrophys.* 289,607.

Solem, J. C. (1994). *Nature* 370, 349.

Weaver, 11. A. (1994a). *IAU Circ. No,* 5947,

Weaver, H. A. (1994b). *IAU Circ. No.* 5973.

Weaver, 11. A. *et* al. (1994). Science 263, 787.